SQ-Phenology: BioMA-*SiriusQuality* component of wheat phenology

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Summary

This document describes the procedure used in the *SQ-Phenology* crop model component (He *et al*., 2012; Baumont *et al*., 2019) to determine, the timing of wheat developmental phases, the phyllochron, the number of leaves on mainstem, the final leaf number, and the number of tillers. Vernalization progress may be taken into account depending on the considered cultivar. The model is integrated in the wheat crop model SiriusQuality3 *(Martre et al., 2006; Martre and Dambreville, 2018)* as an independent component. This component is developed in the public domain software framework BioMA (Biophysical Model Applications). BioMA is developed using Microsoft C# language in .Net framework (version 4.5). The component was coded using the development environment Microsoft Visual Studio 2013. A console application is available to enlighten the practical use of the component.

Contents

1. Theoretical background

Responding to environmental factors the apical meristem of the wheat shoot switches from a vegetative phase where it produces leaf primordia to a reproductive phase where it produces floral primordia. The successive appearance of leaves on the mainstem and tillers is the expression of the vegetative development, while anthesis is a particular stage in the reproductive development of wheat plants. Vegetative and reproductive development are coordinated and overlap in time (Kirby, 1990; Hay & Kirby, 1991), so that much of the reproductive development occurs early in unison with vegetative development. This means that, as far as timing of events is concerned, vegetative and reproductive processes are not independent. Within this framework, in the phenology model proposed by (Jamieson*et al.*, 1998), the variations associated with vernalization requirement and daylength sensitivity are described in terms of primordium initiation, leaf production, and final mainstem leaf number.

The leaf production phase is modeled based on two independently controlled processes, leaf initiation (primordia formation) and emergence (leaf tip appearance) rates and organ identity defining the fate of the apex primordia whether vegetative or reproductive. The interaction between these processes leads to the determination of the final number of leaves that will be produced on the mainstem. Leaf production may follow a segmented linear model in thermal time (Boone *et al.*,1990; Jamieson *et al.*, 1995; Slafer & Rawson, 1997; González *et al.*, 2002) corrected by a surrogate factor for the apex-air temperature effect which depends on sowing date. Leaf production can also depend on the soluble carbohydrate economics (Baumont et al., 2019). The Photothermal Quotient (PTQ) was found to well represent the balance between carbohydrate offer (or amount of intercepted light) and growth demand (or accumulated thermal time).
At any time during vegetative development apex primordia number is calculated through a simple metric relationship with leaf number (Kirby, 1990). Concomitant processes governing apical progress towards a reproductive state and defining the final leaf number (i.e. vernalization requirements and photoperiodic responses) are modeled sequentially. Previous works indicate that the vernalization requirement of some winter wheat genotypes can be eliminated or greatly reduced by a prolonged exposure to short photoperiods (Evans, 1987; Dubcovsky *et al.*, 2006), a process referred in the literature as short day vernalization. The photoperiodic effect on the vernalization rate is likely to involve a quantitative interaction with temperature rather than a complete replacement of the vernalization requirement (Brooking & Jamieson, 2002; Allard *et al.*, 2012).

The crop responds to daylength only once vernalization is complete (or at emergence for a spring cultivar for which the vernalization routine is skipped). It is assumed that daylength sensitivity leads to an increase in the number of leaf primordia resulting from the vernalization routine. If the daylength of the day when vernalization is completed exceeds a given value, then the final number of leaves is set to the value calculated at the end of the vernalization routine (Brooking *et al.*,1995). If not, Brooking *et al.* (1995) have shown that the final leaf number is determined by the daylength at the stage of two leaves after the flag leaf primordium has been formed.

2. Overview of the calculation procedure

Figure 1 shows the flowchart of the *SQ-Phenology* component. It is composed of nine simple strategies and a composite one. First, the sowing correction for phyllochron is calculated (CalculateSowingDateCorrection). Then the potential final leaf number is assessed, the vernalization may progress (CalculateVernalisation Progress), the plant developmental phase is updated and the final leaf number is calculated (UpdatePhase). If the anthesis stage is not reach yet, the leaf number is calculated (CalculateLeafNumber) and the state of the flag leaf is updated (UpdateLeafFlag). There two alternative models to calculate phyllochron, one using the phototehermal quotient (CalculatePhyllochronWithPTQ), the other a segmented linear model (CalculatePhyllochron) with sowing date correction. Finally, the Zadok stage (Zadok *et al*., 1974) is determined (RegisterZadock), the number of tillers is calculated (CalculateShootNumber) and results are exported via the composite class. This procedure is called daily. In what follows each section refers to one of the strategies described above.

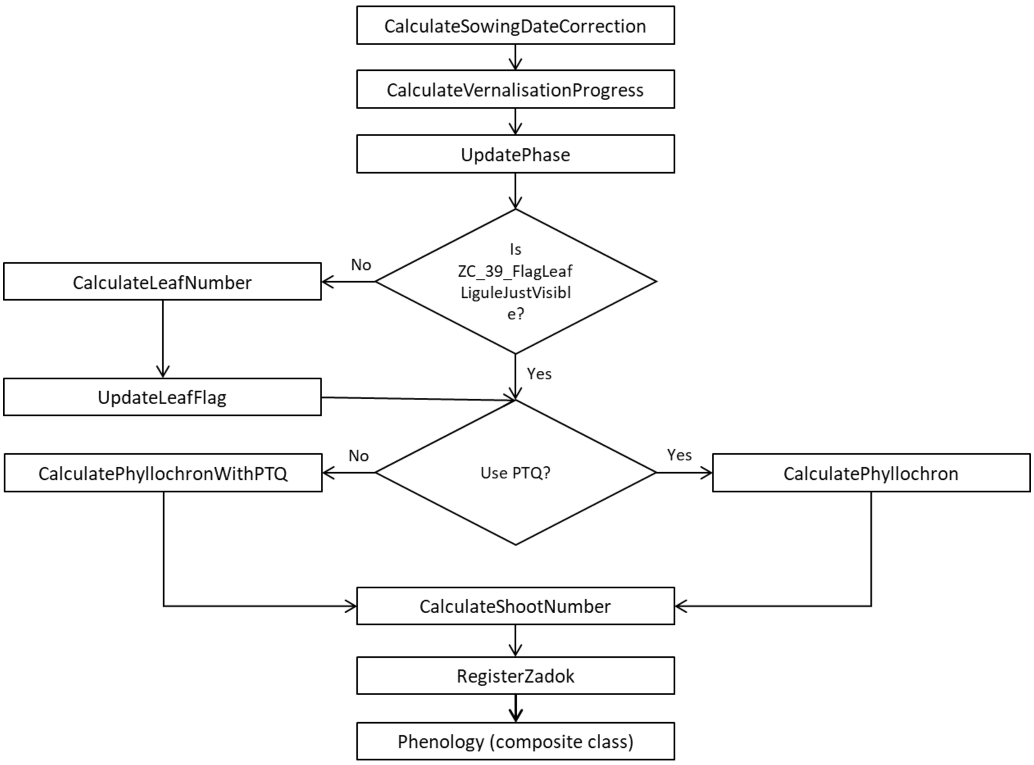

Figure 1. Shema of the BioMA-*SiriusQuality SQ-Phenology* component.

3. Sowing date correction for phyllochron

Many studies have shown that phyllochron depends on the sowing date, several authors have discussed putative physiological causes of theses variations (Slafer & Rawson, 1997; McMaster *et al.*, 2003); while others have shown that most of the observed variations in phyllochron are due to apex-air temperature differences (Vinocur & Ritchie, 2001; Jamieson *et al.*, 2008). In Sirius, as a surrogate for the apex-air temperature correction, for a winter sowing (day of the year 1 to 90 for the Northern hemisphere), the phyllochron decreases linearly with the sowing date and is minimum until mid-July for the Northern hemisphere (day of the year 200). The phyllochron corrected for the sowing date is given as:

$$Phyll_{SD} = \begin{cases} Phyll_{par} \times \left(1 - R_p \times Min\left(SD, SD_{w/s}\right)\right), & 1 \leq SD < SD_{S/A\_nh} \\ Phyll_{par}, & SD \geq SD_{S/A\_nh} \end{cases} \quad (1)$$

where, *SD* is the sowing date in day of the year; $\boldsymbol{Phyll_{par}}$ is a varietal parameter defining the phyllochron for autumn sowing; R_P is the rate of decrease of $Phyll_{SD}$ for winter sowing; $SD_{W/S}$ and SD_{S/A_nh} are the sowing dates for which $Phyll_{SD}$ is minimum and maximum, respectively. Similarly, in the Southern hemisphere where seasons are the opposite the correction becomes:

$$Phyll_{SD} = \begin{cases} Phyll_{par} \times \left(1 - R_p \times Min\left(SD - SD_{S/A\_sh}, SD_{w/s}\right)\right), & SD > SD_{S/A\_sh} \\ Phyll_{par}, & 1 \leq SD \leq SD_{S/A\_sh} \end{cases} \quad (2)$$

SD_{S/A_sh} has a value of 151 days and is defined as the sowing date for which $\boldsymbol{Phyll_{SD}}$ is maximum in the southern hemisphere.

4. Vernalization progress and potential final leaf number

At any time during vegetative development apex primordia number (*PN*) is calculated through a simple metric relationship with leaf number (Kirby, 1990) under the assumption that the apex contains *PNini* primordia at emergence and that they accumulate at twice the rate of leaf emergence (Brooking *et al.*, 1995; Jamieson *et al.*, 1995):

$$PN = 2 \times LN + PNini \quad (3)$$

where, *LN* the number of emerged leaves on the mainstem.

Concomitant processes governing apical progress towards a reproductive state and defining the final leaf number (i.e. vernalization requirements and photoperiodic responses) are modeled sequentially. In the strategy described here only vernalization is considered, photoperiodic response will be presented in the next section.

Vernalization commences once the seed has imbibed water. Previous work indicates that the vernalization requirement of some winter wheat genotypes can be eliminated or greatly reduced by a prolonged exposure to short photoperiods (Evans, 1987; Dubcovsky *et al.*, 2006), a process referred in the literature as short

day vernalization. The vernalizing effect of short days was introduced in *SiriusQuality* to improve the simulation of anthesis date in the hot-serial-cereal experiment (White *et al.*, 2011).
The daily vernalization rate (V_{rate}) increases at a constant rate (VAI) with the daily thermal time increment (TT_{shoot}) from its value (*VBEE*) at the minimum vernalizing temperature (T_{min}^{ver}) to a maximum for an intermediate temperature (T_{int}^{ver}). Above this temperature V_{rate} reduces to zero at the maximum vernalizing temperature (T_{max}^{ver}). TT_{shoot} is an output of the BioMa *SQ-ThermalTime* component. It is calculated as a daily cosinusoidale integration between the maximum and minimum canopy temperature (see *SQ_EnergyBalance* component) and includes the plant growth response with a base temperature of 0°C. The photoperiodic effect on the vernalization rate is likely to involve a quantitative interaction with temperature rather than a complete replacement of the vernalization requirement (Brooking & Jamieson, 2002; Allard *et al.*, 2012). It is modelled following Sirius vernalization framework, with the assumption that the effectiveness of short days decreases progressively as photoperiods increase from DL_{min}^{vern} to DL_{max}^{vern}:

$$V_{rate} = \begin{cases} VAI \times TT_{shoot} + VBEE, & T_{min}^{ver} \le TT_{shoot} \le T_{int}^{ver} \\ Max\left(\begin{array}{c} 0, (VAI \times T_{int}^{ver} + VBEE) \\ \times \left(1 + \frac{T_{int}^{ver} - TT_{shoot}}{T_{max}^{ver} - T_{int}^{ver}} \times \frac{DL_{eff}^{ver} - DL_{min}^{ver}}{DL_{max}^{ver} - DL_{min}^{ver}}\right) \end{array} \right), & T_{int}^{ver} < TT_{shoot} < T_{max}^{ver} \end{cases} \tag{4}$$

where the effective photoperiod ($\boldsymbol{DL_{eff}^{ver}}$) is:

$$DL_{eff}^{ver} = Max(DL_{min}^{ver}, \min(DL_{max}^{ver}, DL)) \tag{5}$$

where, *DL* is the day length. The progress toward full vernalization (V_{prog}) is simulated as a time integral:

$$\boldsymbol{V_{prog}} = \textstyle\sum_{\boldsymbol{day=1}}^{\boldsymbol{n}} \boldsymbol{V_{rate}} \text{ with, } \boldsymbol{V_{prog}} \in [\mathbf{0}, \mathbf{1}] \tag{6}$$

Two non-varietal parameters define the minimum (L_{min}^{abs}) and maximum (L_{max}^{abs}) number of leaves that can emerge on the mainstem. The model assumes that plants start their life with a high potential leaf number (LN_{pot} set to an initial value of L_{min}^{abs}) which decreases with vernalization progress:

$$\boldsymbol{LN_{pot}} = \boldsymbol{L_{max}^{abs}} - (\boldsymbol{L_{max}^{abs}} - \boldsymbol{L_{min}^{abs}}) \times \boldsymbol{V_{prog}} \tag{7}$$

Vernalization is completed when one of the following three conditions is met: 1) V_{prog} has reached a value of 1; 2) LN_{pot} has reached a value that equals L_{min}^{abs}; or 3) LN_{pot} has reduced to *PN*. These primordia are all assumed to produce leaves.

5. Phase update and final leaf number

Several conditions drive the transition from one phase to another. Most of the time, changes happen when the accumulated physiological thermal time of the organs (apex or grain) exceeds a certain value fixed by a parameter. In the case of the transition from emergence to floral initiation the vernalization progress, the photoperiod and the final leaf number are involved.

The pre-emergence phase (Sowing to Emergence) ends when the shoot thermal time accumulated since sowing exceeds the parameter *Dse* which may differ between cultivars (Weir *et al.*, 1984). The apex thermal time is calculated on the basis of the plant growth physiological response to daily mean shoot temperature in the *SQ-ThermalTime* component with a base temperature of 0°C (Maiorano *et al.*, 2017). The shoot temperature is taken as the value of the soil surface until *MaxLeafSoil* leaves (which equals 4 leaves) have emerged on the mainstem (in fact 3 leaves are fully emerged and the tip of the forth is just visible) and subsequently as the canopy temperature, the latter being determined in the *SQ-EnergyBalance* component (Jamieson et al., 1995a: Maiorano *et al.*, 2017).

If the plant is not vernalizable (i.e. spring cultivars) the floral initiation occurs just after the emergence phase. In the other cases photoperiod has to be taken into account. The crop responds to *DL* only once vernalization is completed. It is assumed that *DL* sensitivity leads to an increase in the number of leaf primordia resulting from the vernalization routine. *DL* is calculated in the *SQ-Meteorology* component. If *DL* of the day when vernalization is completed exceeds a given value (DL_{sat}), the final leaf number on mainstem (LN_f) is set to the value calculated at the end of the vernalization routine (Brooking *et al.*,1995) and the floral initiation is reached. For *DL* shorter than DL_{sat}, Brooking *et al.* (1995) have shown that LN_f is determined by *DL* at the stage of two leaves after the flag leaf primordium has been formed. This creates the need for an iterative calculation of an approximate final leaf number (LN_{app}) that stops when the required leaf stage is reached:

$$LN_{app} = Max(LN_{pot}, LN_{pot} + SLDL \times (DL_{sat} - DL)) \quad (8)$$

where, *SLDL* is a varietal parameter defining the day length response as a linear function of *DL*. The attainment of the stage “two leaves after flag leaf primordium” is reached when half of leaves have emerged (Brooking *et al.*, 1995):

$$0.5 \times LN_{app} \leq LN, \text{ then } LN_f = LN_{app} \quad (9)$$

where, *LN* is the leaf number on the mainstem of the considered day. When this condition is fulfilled, transition to floral initiation is completed.

Heading and anthesis are modeled similarly to the emergence phase. Estimation of the heading date is performed only if the Zadok stage 39 (i.e. flag leaf ligule just visible) has been registered (see section 10). The thermal time duration between heading or anthesis since the flag leaf ligule emergence ($TT\_To\_Heading$ and $TT\_To\_Anthesis$) are proportional to the cultivar phyllochron (Brooking *et al.*, 1995) and phyllochronic durations are set as non-varietal parameters:

$$TT\_To\_Heading = (PFLLAnth - PHEADANTH) \times \mathrm{Phyll_{SD}} \quad (10)$$

$$TT\_To\_Anthesis = PFLLAnth \times \mathrm{Phyll_{SD}} \quad (11)$$

where, $PFLLAnth$ and $PHEADANTH$ are the phyllochronic duration of the period between flag leaf ligule appearance and anthesis and between heading and anthesis, respectively.

After anthesis, the development continues until grain ripeness maturity. Grain thermal time is defined as the physiological thermal time accumulated by the shoot since anthesis. The first grain development phase correspond to the endosoperm cell division phase and last a thermal time duration of D_{cd}. Then, grains are filled until completion (End of Cell Division to End of Grain Filling phase). This phase lasts a thermal time duration of D_{gf} (varietal parameter) or until the green area index of the plant equals zero. The grains are finally considered mature when the thermal time accumulated since the end of grain filling exceeds the varietal parameter D_{egmf}. In *SiriusQuality* this drying phase is optional.

In *SiriusQuality* developmental phases are identified by a unique number. Table 1 summarize the different phases and the value of their corresponding code.

Table 1. *SiriusQuality* developmental phases and their corresponding code. See section 10 for definitions.

Growth stage	**Developmental phases**
Sowing	0
Emergence	1
Floral Initiation	2
Heading	3
Anthesis	4
End of Cell Division	4.5
End of Grain Filling	5
Maturity	6

6. Mainstem Leaf appearance

Leaves appear on the mainstem between emergence and Zadok stage 39 under the influence of the daily shoot thermal time increase ($\boldsymbol{TT_{shoot}}$). The leaf number (LN) is incremented daily proportionally to the leaf appearance rate:

$$LN = LN + \frac{TT_{shoot}}{Phyll} \tag{12}$$

where, *Phyll* is the Phyllochron (see section 8).

7. Flag leaf state update

For the purpose of making the leaves stop to emerge, the time when the flag leaf ligule appears has to be identify. This moment is registered when LN becomes larger or equal to LN_f (see section 5).

8. Phyllochron

7.1 Original Sirius phyllochron model

Originally in *SiriusQuality*, leaf production follows a segmented linear model in thermal time taken from the wheat model Sirius (Jamieson *et al.*, 1995). The first two leaves appear more rapidly than the next six, and then leaf appearance slows again for the subsequent leaves independently of the total number of leaves produced. As a result, the phyllochron (that is the leaf appearance rate) is expressed as follows:

$$Phyll = \begin{cases} Pdecr \times Phyll_{SD}, & LN < LN_{decr} \\ Phyll_{SD}, & LN_{decr} \le LN < LN_{incr} \\ Pincr \times Phyll_{SD}, & LN \ge LN_{incr} \end{cases} \quad (13)$$

where, $Phyll_{SD}$ is the genotypic parameter defining the phyllochron corrected by sowing date effects to mimic an apex-air temperature difference correction (see section 1). Other parameters are non-varietal. If the actual number of visible leaves on the mainstem (*LN*) is lower than $\boldsymbol{LN_{decr}}$ the phyllochron is decreased by $Pdecr$. If it is larger than LN_{incr} it is increased by $Pincr$. Note that *LN* can be seen as the Haun stage (Haun, 1973).
For test purposes it is possible not to apply the $Phyll_{SD}$ correction. The Phyllochron then writes:

$$Phyll = \begin{cases} Pdecr \times Phyll_{par}, & LN < LN_{decr} \\ Phyll_{par}, & LN_{decr} \le LN < LN_{incr} \\ Pincr \times Phyll_{par}, & LN \ge LN_{incr} \end{cases} \quad (14)$$

and, for example, it is possible to work with a linear model of leaf appearance rate by setting *Pdecr* and *Pincr* value to unity. A special BioMa strategy is dedicated to this calculation, but the strategy is not mention in this document for the sake of clarity.

7.2 Calculation from photothermal quotient (PTQ)

This model of phyllochron relies on four hypothesis (Baumont et al., 2019): (1) the leaf appearance rate (LAR) depends on the supply-to-demand ratio for soluble carbohydrate, estimated by the ratio of intercepted light to thermal time; (2) the demand for soluble carbohydrate is proportional to plant size and this proportionality can be approximated by the green area index; (3) soluble carbohydrates in the plant provide a buffering capacity to fluctuating environments in the field; and (4) leaves are able to maintain a minimum rate of development. The model is given as:

$$\frac{1}{Phyll} = \mathrm{LAR} = \frac{\mathrm{LAR_{min}} + \left(\frac{(\mathrm{LAR_{max}} - LARmin) \times PTQ}{\mathrm{PTQ_{hf}} + PTQ}\right)}{\alpha \times \mathrm{GAI_{eff}}} \quad (15)$$

where, $PTQ = \overline{I_{\mathrm{int}}}(d)/\overline{T_{\mathrm{t}}}(d)$ with $\overline{I_{\mathrm{int}}}(d)$ the cumulative PAR intercepted by the canopy during the period d and $\overline{T_{\mathrm{t}}}(d)$ the thermal time accumulated during the period d. $\overline{\mathrm{GAI}}_{\mathrm{eff}}$ is the average green area fraction over the period d, and α is an empirical parameter that scales carbon demand to GAI. $\mathrm{LAR_{min}}$ is the minimum

LAR when PTQ equals zero, $\mathrm{LAR_{max}}$ is the maximum appearance rate when PTQ tends to infinity, and $\mathrm{PTQ_{hf}}$ is the PTQ when LAR is half its maximum. LAR tends to infinite when GAI tends to 0. Therefore, a minimum value of $\overline{\mathrm{GAI}}_{\mathrm{eff}}$ was considered as the potential GAI when Haun stage equals 3 and the first tiller has appeared. $\overline{\mathrm{GAI}}_{\mathrm{eff}}$ is given as:

$$\overline{\mathrm{GAI}}_{\mathrm{eff}} = \begin{cases} LN_{\mathrm{eff}} \times A_{\mathrm{L_{juv}}}^{pot} \times \mathrm{PD} \times 10^3, & LN < LN_{\mathrm{eff}} \\ Max_{em\_mat}(\overline{\mathrm{GAI}}(d)), & LN \geq LN_{\mathrm{eff}} \end{cases} \tag{16}$$

where, $A_{\mathrm{L_{juv}}}^{pot}$ is the potential surface area of juvenile leaves, as defined in the *SiriusQuality* leaf growth model (Martre and Dambreville*,* 2018)*,* PD is the plant density, LN is the number of mainstem emerged leaves, and $\mathrm{LN_{eff}}$, the number of mainstem leaves above which the demand for respiration increases relatively to sink formation. The factor 10^3 allows converting cm² to m². $Max_{em\_mat}\overline{\mathrm{GAI}}(d)$ is the maximum green area index fraction averaged over the period *d* since emergence. The maximum value of $\overline{\mathrm{GAI}}(d)$ is taken so that $\overline{\mathrm{GAI}}_{\mathrm{eff}}$ does not decrease is the rate of senescence of the youngest leaves if higher than the expansion of the growing leaves.

In Eq. (5) environmental variables are averaged over several days to account for the buffering effect of stored soluble carbohydrates. The fraction of light intercepted by the crop during the period d is given as (Monsi and Saeki, 2005):

$$\overline{I_{\mathrm{int}}}(d) = \sum_{i=1}^{d} I_0(i)\left(1 - e^{-K_{\mathrm{L}}\mathrm{GAI}(i)}\right) \tag{17}$$

where, I_0 is the incident daily photosynthetic active radiation and k_{L} is the light extinction coefficient. The thermal time during the period d is given as:

$$\overline{T_{\mathrm{t}}}(d) = \sum_{i=1}^{d} TT_{shoot}\,(i) \tag{18}$$

9. Shoot number

The potential number of shoots (main stem + tillers) per plant (*NT*) is first calculated as a function of the number of leaves emerged on mainstem (*LN*) and is assumed to follow a Fibonacci sequence (Kirby, 1985):

$$NT_{LN+2} = NT_{LN+1} + NT_{LN} \tag{19}$$

$\boldsymbol{NT_{LN+2}}$ corresponds to the stage where two extra leaves have appeared and equals the number of shoots during the previous stage (when *LN+1* leaves were on the mainstem) added to the original number of tillers (when the number of leaves was *LN*). The calculation of *NT* is recursive and the number of tillers corresponding to *LN = 1* and *LN = 2* are $\boldsymbol{NT_1 = 1}$ and $\boldsymbol{NT_2 = 1}$, repectively. first order tillers appear when *LN = 3,* second order tiller when *LN = 4* and so on*.* Following this progression, the shoot number for one plant is $\boldsymbol{NT_1 = NT_2 = 1}$ when *LN*≤2, $\boldsymbol{NT_3 = NT_2 + NT_1 = 2}$ when *LN*=3 and $\boldsymbol{NT_4 = NT_3 + NT_2 = 2 + 1}$ when *LN*=4.

The shoot number is then multiplied by the plant density (*PD*) to obtain a mean shoot number per square meter (NT_{pot}). In field plant to plant competition and local heterogeneity in plant density and resources often results in small variations of final tiller number *(*Martre and Dambreville, 2018*)*. Therefore, here, we do not attempt to explicitly model the cessation of tillering and tiller death. Instead, we assumed that canopies can have a constant maximum number of fertile tillers of (*TargetFertileShoot*) and we consider only the appearance of new tillers below this threshold. The actual shoot density (NT_{act}) at a given time is then:

$$NT_{act} = Min(NT_{pot}, TargetFertileShoot) \tag{20}$$

As a result, if one consider a plant density equals to *PD*=200 plants m^{-2} and a final number of fertile shoots of 550 tillers m^{-2}, then the modeled crop will produce 200 mainstems (corresponding to $\boldsymbol{NT_2 \times PD}$) and first order tillers per square meter (corresponding to $\boldsymbol{(NT_3 - NT_2) \times PD}$) and 150 second order tillers per square meter (corresponding to $\boldsymbol{Min(NT_{3+1} \times PD, TargetFertileShoot) - (NT_2 + NT_3) \times PD}$.

10. Zadok stages

In addition to the developmental phases presented in section 5, Zadok stages (or equivalent) are registered along with the cumulated shoot physiological thermal time from sowing to the beginning of the stage. The date the stage has been reached is also stored. Table 2 enumerates the considered developmental stages and their definition.

Table 2. *SiriusQuality* growth stages and their definition.

Zadok stage	Description
ZC_00_Sowing	Germination (Zadok 00 to 09): From dry seed to leaf just at coleoptile tip
ZC_10_Emergence	Seeding development (Zadok 10 to 19): For Zadok stage 10 the tip of the first leaf is visible on main stem
EndVernalisation	Tillering (Zadok 20 to 29): End of the vernalization period and main shoot only
ZC_21_MainShootPlus1Tiller	Tillering: First tiller has appeared
FloralInitiation	Apex differentiates and can become future leaves or future flowers
ZC_22_MainShootPlus2Tiller	Tillering: Second tiller has appeared
TerminalSpikelet	The full complement of spikelets has been initiated at the shoot apex
ZC_30_PseudoStemErection	Stem elongation or jointing (Zadok 30 to 39): The nodes and the growing point move upward from the crown to produce long stiff stem that will carry the head. This is the first phase of that process.

ZC_23_MainShootPlus3Tiller	Tillering: third tiller has appeared
BeginningStemExtension	Stem elongation or jointing: The nodes from which leaves develop are telescoped at the crown during the tillering stage. Once jointing starts, the internode region elongates
ZC_31_1stNodeDetectable	Stem elongation or jointing: The first node can be detected without dissecting the plant
ZC_32_2ndNodeDetectable	Stem elongation or jointing: Second node can be detected
ZC_37_FlagLeafJustVisible	Stem elongation or jointing: the tip of the last leaf just before the ear (flag leaf) is visible
ZC_39_FlagLeafLiguleJustVisible	Stem elongation or jointing: Flag leaf ligule/collar has just appeared
ZC_55_Heading	Zadok stages from 50 to 59: The heading stage extends from the time of emergence of the tip of the head from the flag leaf sheath to when the head has completely emerged but has not yet started to flower
ZC_65_Anthesis	Anthesis (Zadok 60 to 69): Pollination and fertilization occur during this period. All heads of a properly synchronized wheat plant flower within a few days and the embryo and endosperm begin to form immediately after fertilization. Anthesis is half completed at Zadok stage 65
ZC_75_EndCellDivision	Milk stages (Zadok 71 to 77): Early kernel formation occurs during the milk stage. The developing endosperm starts as a milky fluid that increases in solids as the milk stage progresses. Kernel size increases rapidly during this stage. Stage Zadok 75 corresponds to the end of endosperm cell division
ZC_85_MidGrainFilling	Dough Stages (Zadok 83 to 87): Kernel formation is completed during the dough development stage. The kernel accumulates most of its dry weight during dough development. Zadok stage 85 corresponds to the soft dough, before the transport of nutriments from the leaves, stems and spike to the developing grain is completed (hard dough). During this stage the endosperm endoreduplication ends
ZC_91_EndGrainFilling	Ripening stages (Zadok 91 to 99). Zadok 91 corresponds to a hard kernel when it is difficult to separate grains by fingernail
ZC_92_Maturity	Ripening stages: Grains are dry

When no phase (see section 5) has been defined for a Zadok stage, the latter is determined from the plant Haun stage (equivalent to the number of visible leaf tips on mainstem) or special conditions related to the nature of the stage. Table 3 summarize the conditions to reach the different growth stages.

Table 3. *SiriusQuality* developmental stages and conditions to attain them.

Zadok stage	**Condition**
ZC_00_Sowing	Initial stage at the beginning of the simulation and phase value = 0

ZC_10_Emergence	Phase value = 1
EndVernalisation	The variety is vernalizable and $V_{prog} \geq 1$ or $PN \geq L^{abs}_{max}$ or $PN \geq LN_{pot}$ (see equations 6 and 7)
ZC_21_MainShootPlus1Tiller	Leaf number = 4
FloralInitiation	Phase value = 2
ZC_22_MainShootPlus2Tiller	Leaf number = 5
BeginningStemExtension	The last internode created has a length larger than zero
TerminalSpikelet	$LN = slopeTSFLN \times LN_f - intTSFLN$
	With *LN* the leaf number, LN_f the final leaf number and $slopeTSFLN$ and $intTSFLN$ two non-varietal parameters corresponding to the slope and the intercept of the linear relationship between Haun stage at terminal spikelet and final leaf number, respectively
ZC_30_PseudoStemErection	Four leaves before their final number have grown
ZC_23_MainShootPlus3Tiller	Leaf number = 6
ZC_31_1stNodeDetectable	Three leaves before their final number have grown
ZC_32_2ndNodeDetectable	Two leaves before their final number have grown
ZC_37_FlagLeafJustVisible	One leaf before the final number has grown
ZC_39_FlagLeafLiguleJustVisible	Leaf number equals to final leaf number
Heading	Phase value = 3
ZC_65_Anthesis	Phase value = 4
ZC_75_EndCellDivision	Phase value = 4.5
ZC_85_MidGrainFilling	Phase value = 4.5 and the accumulated shoot thermal time since anthesis is larger than the parameter *Der* (Duration of the endosperm endoreduplication)
ZC_91_EndGrainFilling	Phase value = 5
ZC_92_Maturity	Phase value = 6

While phases defined in section 5 are actual benchmarks for *SiriusQuality* simulations, Zadok stages without phase correspondence are only used as time markers in the output files for comparison with observations.

11. References

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12. Appendix

Table A1. List of variables used in the *SQ-Phenology* component.

Symbol	Name in the code	Unit	Description	Equation	Strategy
$Phyll_{SD}$	Fixphyll	°Cd/leaf	Surrogate for the apex-air temperature correction of the phyllochron parameter ($Phyll_{par}$)	(1) (2) (13) (10) (11)	*CalculatePhylSowingDateCorrection* *CalculatePhyllochron*
PN	primordno	-	Apex primordia number	(3)	*CalculateVernalizationProgress*
LN	LeafNumber	leaf	Number of emerged leaf on mainstem	(9) (12) (13) (14) (16) (19)	*CalculateLeafNumber* *CalculatePhyllochron* *CalculateShootNumber* *CalculateVernalizationProgress* *RegisterZadok* *UpdateLeafFlag* *CalculateLeafNumber* *CalculatePhyllochron*
TT_{shoot}	DeltaTT	°Cd	Shoot physiological thermal time of the day	(4) (12) (18)	*CalculateLeafNumber* *CalculateVernalizationProgress*
V_{rate}	-	1/day	Vernalization rate	(4) (6)	-
DL	DayLength	hour	Photoperiod	(5) (8)	*CalculateVernalizationProgress* *UpdatePhase*
DL_{eff}^{ver}	DLverna	hour	Effective photoperiod	(4) (5)	*CalculateVernalizationProgress*

V_{prog}	Vernaprog	-	Vernalisation Progress	(6) (7)	*CalculateVernalizationProgress* *UpdatePhase*
LN_{pot}	potlfno	Leaf	Potential final leaf number	(7) (8)	*CalculateVernalizationProgress* *UpdatePhase*
LN_{app}	appFLN	leaf	Approximated final leaf number	(8) (9)	*UpdatePhase*
LN_{f}	FinalLeafNumber	leaf	Final leaf number	(9)	*UpdatePhase* *UpdateLeafFlag* *Register Zadok*
TT_To_Heading	ttFromLastLeafToHeading	°Cd	Thermal time accumulated from the emergence of flag leaf to heading	(11)	*UpdatePhase*
TT_To_Anthesis	ttFromLastLeafToAnthesis	°Cd	Thermal time accumulated from the emergence of flag leaf to anthesis	(10)	*UpdatePhase*
Phyll	Phyllochron	°Cd/leaf	Phyllochron from segmented linear model	(12) (13) (14) (15)	*CalculatePhyllochron* *CalculateLeafNumber*
LAR	LAR	leaf/°Cd	Leaf appearance rate	(15)	*CalculatePhyllochronWithPTQ*
PTQ	PTQ	MJ(PAR)/m²/°Cd	PhotoThrermal Quotient	(15)	*CalculatePhyllochronWithPTQ* *CalculatePTQ*
GAI_{eff}	GAILim	m²(leaf)/m²(soil)	Potential GAI when *LN=LNeff*	(15) (16)	*CalculatePhyllochronWithPTQ*
$\overline{\mathrm{GAI}}(d)$	GAImean	m²(leaf)/m²(soil)	Canopy Green Area Index averaged on the *TTWindowForPTQ* thermal time interval	(16)	*CalculatePhyllochronWithPTQ* *CalculateGAImean*
GAI	GAI	m²(leaf)/m²(soil)	Canopy Green Area Index of the day	(17)	*CalculateGAImean* *CalculatePTQ*

I_0	PAR	MJ(PAR)/m²/d	Incident Photosynthetically Active Radiation of the day	(17)	*CalculatePTQ*
$\overline{I_{\mathrm{int}}}(d)$	parInt	MJ(PAR)/m²	Intercepted Photosynthetically Active Radiation summed on the *TTWindowForPTQ* thermal time interval	(17)	*CalculatePTQ*
$\overline{T_{\mathrm{t}}}(d)$	TTShoot	°Cd	Phsiological thermal time summed on the *TTWindowForPTQ* thermal time interval	(18)	*CalculateGAImean* *CalculatePTQ*
NT	Shoots	-	Shoot number (mainstem + tillers) per plant	(19)	*CalculateShootNumber*
NT_{pot}	-	m^{-2}	Potential shoot (mainstem +tiller) density	(20)	*CalculateShootNumber*
NT_{act}	CanopyShootNumber	m^{-2}	Actual shoot (mainstem +tiller) density	(20)	*CalculateShootNumber*

Table A2: List of parameters and constants used in the *SQ-Phenology* component. Parameter values are given for the spring wheat cultivar Yecora Rojo.

Symbol	Name in the code	Nominal value	Unit	Description	Equation
$Phyll_{par}$	P	120	°Cd/leaf	Phyllochron of the variety (varietal)	(1) (2) (14)
SD	SowingDay	80	day of the year	Sowing date	(1) (2)
R_p	Rp	0.003	1/day of year	Rate of change of phyllochron with sowing date	(1) (2)
$SD_{W/S}$	SDws	90	day of year	Sowing date at which Phyllochron is minimum	(1) (2)
SD_{S/A_nh}	SDsa_nh	200	day of year	Sowing date at which Phyllochron is maximum in Northern hemisphere	(1)
SD_{S/A_sh}	SDsa_sh	151	day of year	Sowing date at which Phyllochron is maximum in Sourthern hemisphere	(2)
$PNini$	PNini	4	primordium	Number of primordia in the apex at emergence	(3)
VAI	VAI	0.015	1/°Cd	Response of vernalization rate to temperature (Varietal)	(4)
VBEE	VBEE	0.01	1/day	Vernalization rate at 0°C (Varietal)	(4)
T_{min}^{ver}	MinTvern	0	°C	Minimum temperature for vernalization to occur	(4)
T_{max}^{ver}	MaxTvern	23	°C	Maximupm temperature for vernalization to occur	(4)
T_{int}^{ver}	IntTvern	11	°C	Intermediate temperature for vernalization to occur	(4)
DL_{min}^{ver}	MinDL	8	hour	Threshold day length below below which it does not influence vernalization rate	(4) (5)
DL_{max}^{ver}	MaxDL	15	hour	Saturating photoperiod above which final leaf number is not influenced by day length	(4) (5)
L_{max}^{abs}	AMXLFNO	24	leaf	Absolute maximum leaf number	(7)
L_{min}^{abs}	AMNFLNO	5.5	leaf	Absolute minimum leaf number	(7)
SLDL	SLDL	0.85	Leaf/h (day length)	Day length response of leaf production (Varietal)	(8)

DL_{sat}	MaxDL	15	hour	Saturating photoperiod above which final leaf number is not influenced by daylength	(8)
PHEADANTH	PFLLAnth	2.22	Phyllochron	Phyllochronic duration of the period between flag leaf ligule appearance and anthesis	(10)
PHEADANTH	PHEADANTH	1	Phyllochron	Phyllochronic duration between heading and anthesis	(11)
Dse	Dse	105	°Cd	Thermal time from sowing to emergence (Varietal)	-
Dcd	Dcd	100	°Cd	Duration of the endosperm cell division phase	-
Dgf	Dgf	450	°Cd	Grain filling duration from anthesis to physiological maturity (Varietal)	-
Der	Der	300	°Cd	Duration of the endosperm endoreduplication phase	-
Degfm	Degfm	0	°Cd	Grain maturation duration from physiological maturity to harvest ripeness (Varietal)	-
MaxLeafSoil	MaxLeafSoil	4	leaf	Leaf number up to which the canopy temperature is equal to the soil temperature	-
Pdecr	Pdecr	0.4	-	Factor decreasing the phyllochron for leaf number less than LN_{decr}	(13) (14)
Pincr	Pincr	1.25	-	Factor decreasing the phyllochron fro leaf number larger than LN_{incr}	(13) (14)
LN_{decr}	Ldecr	3	leaf	Leaf number up to which the phyllochron is decreased by Pdecr	(13) (14)
LN_{incr}	Lincr	8	leaf	Leaf number above which the phyllochron is increased by Pincr	(13) (14)
LN_{ieff}	LNeff	3	leaf	Number of mainstem leaves above which the demand for respiration increases relative to sink formation	(16)
LAR_{min}	LARmin		leaf/°Cd	Minimum leaf appearance rate when photothermal quotient equals zero (varietal)	(15)
LAR_{dif}	LARdif		leaf/°Cd	Value to add to $\mathrm{LAR}_{\mathrm{min}}$ to reach maximum leaf appearance rate when photothermal quotient tends to infinite	(15)

PTQ_{hf}	PTQhf		MJ(PAR)/m²/°Cd	Photothermal quotient when leaf appearance rate is half $\mathrm{LAR}_{\mathrm{dif}} + \mathrm{LAR}_{\mathrm{min}}$	(15)
$A_{\mathrm{L_{juv}}}^{pot}$	AreaSL + AreaSS		Cm²	Potential area of small leaves (exposed sheath+laminae)(Varietal)	(16)
d	TTWindowForPTQ	70	°Cd	Thermal Time window for the sliding average of the PTQ calculations	(17) (18)
K_L	Kl	0.45	m²(soil)/m²(leaf)	Light extinction coefficient (vatietal)	(17)
TargetFertileShoot	TargetFertileShoot	600	shoot/m²	Target fertile shoot number	(20)
slopeTSFLN	slopeTSFLN	0.9	-	Slope of the relationship between Haun stage at terminal spikelet and final leaf number	-
intTSFLN	intTSFLN	2.6	leaf	Intercept of the relationship between Haun stage at terminal spikelet and final leaf number	
-	IsVernalizable	1		Integer: 1 the plant is vernalizable, 0 it is not (Varietal)	-
-	Latitude	33.069	degree	Latitude of the field	-
PD	SowingDensity	288.0	1/m²	Density of Sowing	(16)